

## Composition of lunar magma ocean constrained from physical properties of magma: An experimental study

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We report here our attempts to understand differentiation processes in the lunar magma ocean (LMO) based on experimental constraints from physical properties of magma ocean. Many of the key processes in LMO depend on physical and chemical properties of minerals and silicate melts, but some have not yet been precisely determined. Thus, even with a proper model of the magma ocean, it may not necessarily be realistic modeling of LMO. The most critical but poorly constrained parameter is the bulk composition of LMO. We have tried to constrain the composition of LMO by combining the physical modeling of LMO and experimental determination of physical properties of silicate melts. The critical condition is that anorthite can float from the melt that has already fractionated mafic phases at higher temperatures, which requires that (1) there still remains residual melt, (2) the melt has larger density than anorthite, and (3) the viscosity of the melt is small enough to float anorthite even at the final stage of magma ocean crystallization near the surface. Thus, it is crucial to investigate the density and viscosity of melt with the residual melt composition coexisting with anorthite as a function of pressure and bulk composition of LMO.

We first carried out floatation experiments of anorthite in silicate melts with various compositions using a piston cylinder apparatus. We further performed experiments to measure viscosities of the melts.

We have prepared three starting glasses, BSE, CI4 and CI6; (1) Initial bulk LMO compositions were assumed to be BSE (bulk silicate Earth) or to have solar elemental ratios of Si, Al, Mg, and Ca with varying Fe contents (CI4 and CI6). The CI4 and CI6 contain FeO of 4 or 6 wt%, respectively. The former corresponds to the existence of 400-km metallic core for the moon with the bulk CI composition. However, the depletion of siderophile elements for the bulk moon has been widely known, and thus 400 km is the maximum core size for the composition of CI6. The FeO content in the latter case was taken from Smith J. V. and Steele, I. M. (1975). (2) The initial bulk LMO was differentiated at an experimental pressure using the MELTS or pMELTS algorithms until the first appearance of anorthite. (3) The amounts of Na<sub>2</sub>O and TiO<sub>2</sub> for CI4 and CI6 were determined as minimum concentrations, with which MELTS/pMELTS could calculate the liquidus of anorthite at an experimental pressure.

The starting glass was put in a Pt capsule (4.4 mm in inner diameter and 10 mm in height). A few chips of anorthite, which is a natural almost pure, were placed at the middle of the capsule. Experiments were made at 0.5 and 1.0 GPa and at 1300 and 1350°C. Viscosity of CI6 and CI4 melts were measured with the falling-sphere method at 0.5 and 1.0 GPa and at temperatures between 1300 and 1350°C. Run durations ranged 2 - 5 min.

Anorthite floated in melts of all the compositions at 1.0 GPa. At 0.5 GPa, anorthite floated in CI6 and BSE melts; however it did not float in CI4 melt. This is the first that floatation of anorthite in silicate melt with a plausible compositional range of LMO that can coexist with anorthite is experimentally proved.

Viscosities of the CI4 and CI6 melts range from 1.8 to 3.0 Pa.s at pressures between 0.5 and 1.0 GPa (100 and 200 km depths, respectively) and slightly decrease with increasing pressure at constant temperature. Such viscosities are small enough for plagioclase to have floated within a plausible time scale. In the LMO, temperature would have increased with depth, so that it is most probable that the viscosity of LMO further decreased with increasing depth and plagioclase floatation was more efficient with depth.